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Neutrino oscillations in high energy cosmic neutrino flux

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Abstract

I discuss the effects of neutrino oscillations on high energy cosmic neutrinos which come from cosmologically distant astrophysical sources. I incorporate all the up-to-date constraints from the solar, atmospheric, reactor, accelerator data and give the possible pattern for the ratio of the high energy cosmic neutrinos in the cases of three and four neutrino schemes.

1. Introduction

A lot of attention has been focused on high energy neutrinos ($E \geq 10^6$ GeV) which come from cosmologically distant astrophysical sources such as Active Galactic Nuclei and Gamma Ray Burst fireballs (typical distance is 100 Mpc), since they can be distinguished from atmospheric neutrinos for such high energies and identification of flavors of neutrinos may be possible in new km^2 surface area neutrino telescopes [1, 2]. The effects of neutrino oscillations on the high energy cosmic neutrinos have been discussed in the past [1, 4, 5], and the purpose of this talk is to update the analysis by taking into account all the constraints from the solar, atmospheric, reactor and accelerator data in the three or four neutrino framework (This talk is based on the work [6]).

2. Analysis

Since the path length of neutrinos is much larger than any possible neutrino oscillation length which is suggested from the solar, atmospheric or LSND data for the energy $E_\nu \sim 10^6$ GeV, I will average over rapid oscillations throughout this talk. Then the oscillation probability is given by

$$P(\nu_\alpha \to \nu_\beta; L = \infty) = \delta_{\alpha\beta} - \sum_{j \neq k} U^*_{\alpha j} U_{\beta j} U_{\alpha k} U^*_{\beta k} \;\; = \;\; \sum_j |U_{\alpha j}|^2 |U_{\beta j}|^2, \quad (1)$$

where $U_{\alpha k}$ stands for the MNS mixing matrix and I have ignored odd functions in $\sin(\Delta m^2_{ij} L/4E)$ which oscillate rapidly as $L \to \infty$.

The electron and muon neutrinos are mainly produced in the decay chain of charged pions whereas the tau neutrinos are mainly produced in the decay chain of charmed mesons at a suppressed level [3]. The ratio of the intrinsic high energy cosmic neutrinos flux is typically $F^0(\nu_e) : F^0(\nu_\mu) : F^0(\nu_\tau) = 1 : 2 : < 10^{-5}$. For simplicity I assume that the ratio is $F^0(\nu_e) : F^0(\nu_\mu) : F^0(\nu_\tau) = 1 : 2 : 0$. Thus the ratio of flux of neutrinos in the far distance is given by

$$
\begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix} = P \begin{pmatrix} F^0(\nu_e) \\ F^0(\nu_\mu) \\ F^0(\nu_\tau) \end{pmatrix} = P \begin{pmatrix} 1 \\ 2 \\ 0 \end{pmatrix} F^0(\nu_e),
\tag{2}
$$

where a matrix P has components $(P)_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta; L = \infty)$ (See (1)).

Since currently we do not know the precise total cosmic neutrino flux I will mainly focus my discussion on the ratio of different flavors of neutrinos. To plot the ratio of the three neutrino flavors, I introduce a triangle representation. Fig. 1 is a unit regular triangle and the position of the point gives the ratio of the high energy neutrino flux, where $F_\alpha \equiv F(\nu_\alpha)$ is given by (2).

Fig. 1 **Fig. 2**
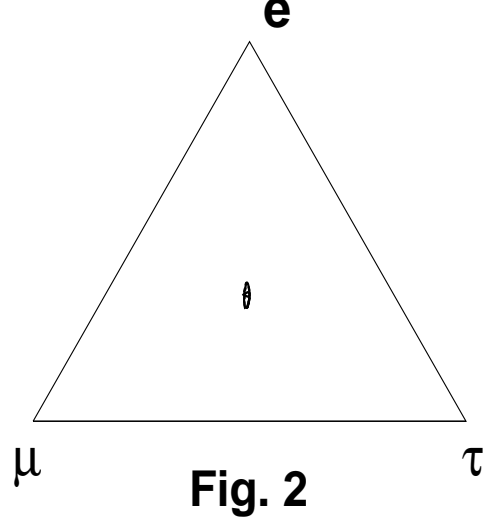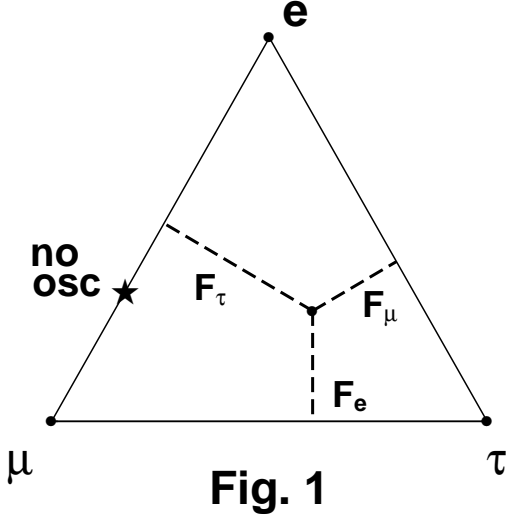
In the three flavor framework, because of the constraint of the CHOOZ data [7] and the atmospheric neutrino data of Superkamiokande and Kamiokande, it has been known that $|U_{e3}|^2$ is small and $|U_{\mu j}|^2 \simeq |U_{\tau j}|^2|$ (See, e.g., [8]). Using the allowed region for $|U_{\alpha j}|^2$ ($\alpha = e, \mu, \tau$) in the atmospheric neutrino analysis of [8] and in solar neutrino analysis of [9], the possible ratio of the high energy neutrino flux is calculated numerically and is given in Fig. 2. The allowed region is a small area around the midpoint $F(\nu_e) = F(\nu_\mu) = F(\nu_\tau) = 1/3$.

Fig. 3

Fig. 4
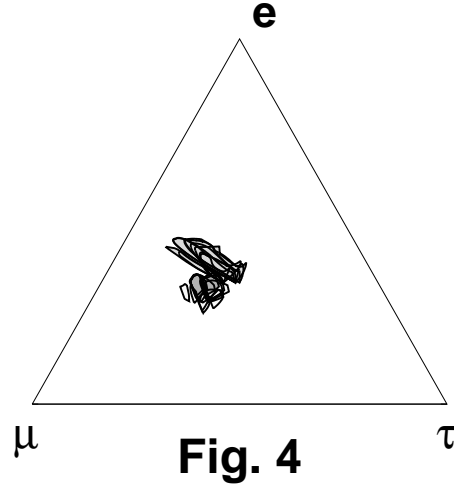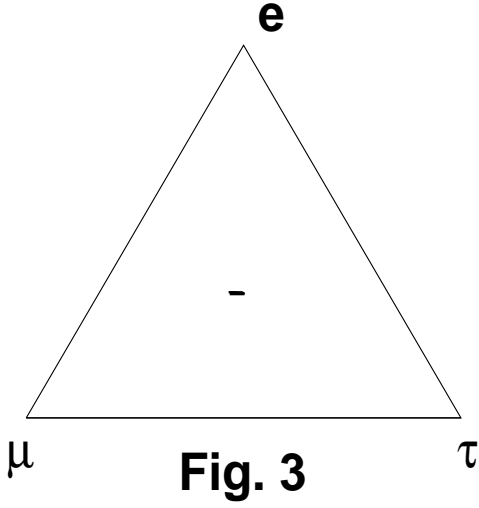
In the four neutrino scheme one needs in principle tetrahedron to express the ratio of the four neutrino flux, but since we do not observe the cosmic sterile neutrino I normalize the flux of each active neutrino by the total flux of active ones:

$$\begin{pmatrix} \widetilde{F}(\nu_e) \\ \widetilde{F}(\nu_\mu) \\ \widetilde{F}(\nu_\tau) \end{pmatrix} \equiv \frac{1}{F(\nu_e) + F(\nu_\mu) + F(\nu_\tau)} \begin{pmatrix} F(\nu_e) \\ F(\nu_\mu) \\ F(\nu_\tau) \end{pmatrix}. \tag{3}$$

After redefining the flux this way ($\widetilde{F} \to F$), we can plot the ratio of each active neutrino with the same triangle graph as in the three neutrino case.

If one demands that the number N_ν of effective neutrinos in Big Bang Nucleosynthesis (BBN) be less than 4, then it can be shown [10] that the 4×4 MNS mixing matrix splits into two 2×2 block diagonal matrices. In this case the ratio is given by a small region depicted in Fig. 3.

On the other hand, some people [11] give conservative bound for N_ν, and without the BBN constraint $N_\nu < 4$ the only restrictions come from the solar and atmospheric neutrino data. The analysis of the solar neutrino data in the four neutrino scheme with ansatz $U_{e3} = U_{e4} = 0$ has been done recently in [12]. The analysis of the atmospheric neutrino data in the four neutrino framework has been done in [13] again with ansatz $U_{e3} = U_{e4} = 0$. Using these results, the ratio of the high energy cosmic neutrinos is evaluated and is given in Fig. 4 which has much wider allowed region than any other case. This scheme may be distinguished from others if one has good precision in future experiments.

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